A New Physics Source of Hard Gluons in Top Quark Production*

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Abstract

We consider the contribution of new strongly interacting sector, with a characteristic scale of half a TeV, to top quark production at the Tevatron. The color-octet, isosinglet analog of the ρ meson in this theory is produced copiously in hadron colliders. If the mass of this resonance is less than twice the mass of the lightest pseudo-Goldstone bosons, then an important decay mode could be to the color-octet analog of the η and a gluon. The subsequent decay of this η into $t\bar{t}$ gives rise to top quark events with a hard gluon.

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Recently the CDF and D0 collaborations have presented evidence confirming the production of top quarks at the Tevatron Collider. CDF [2] finds a top quark mass of $m_t = 176 \pm 8 \pm 10\,\mathrm{GeV}$ and the cross section $\sigma(p\overline{p} \to t\overline{t}) = 6.8^{+3.6}_{-2.4}\,\mathrm{pb}$. D0 [3] finds a mass of $m_t = 199^{+19}_{-21} \pm 22\,\mathrm{GeV}$ and a cross section $6.4 \pm 2.2\,\mathrm{pb}$. For $m_t = 176\,\mathrm{GeV}$ the QCD prediction for the cross section is $\sigma(p\overline{p} \to t\overline{t}) = 4.79^{+0.67}_{-0.41}\,\mathrm{pb}$ [4]. While the CDF value for the cross section is not inconsistent with the QCD prediction, it still leaves some room for contributions to $t\overline{t}$ production from other sources. Thus one would like to explore signals from new physics which may show up in top quark studies.

In this talk we will consider the contribution of a color-octet, isosinglet vector resonance, the ρ_8, to $t\overline{t}$ production. Such a resonance is expected in any strongly interacting theory which has at least one colored, electroweak doublet of fermions. For the most part we consider ρ_8 masses in the 400-600 GeV range, although we shall see that higher values may also be of interest. Examples of theories with masses in this range, which is somewhat below the usual TeV electroweak symmetry breaking scale, are discussed in [5],[6], and [7].

As discussed in [8], the ρ_8 has the odd-parity decay modes $\rho_8 \to \eta_8\mathcal{G}$ and $\rho_8 \to \eta_0\mathcal{G}$. If the color-octet or the color-singlet analogs of the QCD η meson (η_8 or η_0) are above the $t\overline{t}$ threshold, then they decay predominantly into $t\overline{t}$ [9]. A signature to be explored in this talk is provided by the hard gluon produced in addition to the $t\overline{t}$ pair.

The color-octet η_8 itself can be strongly produced in hadronic collisions and its contribution to $t\overline{t}$ production has been considered by several authors [9] – [15]. However this is mainly produced from initial states involving two gluons. At the Tevatron, since we are dealing with processes where the initial partons have a large fraction of the proton's momentum, the gluon distribution functions are much smaller than the quark distribution functions. This leads us to consider the ρ_8 which is produced from $q\overline{q}$ initial states. Since the production cross section for a color-octet ρ_8 is quite large [11, 6], we expect that the process $q\overline{q} \to \rho_8 \to \eta_8\mathcal{G} \to t\overline{t}\mathcal{G}$ could contribute substantially to the top quark production rate at the Tevatron, depending on the masses of the ρ_8 and the η_8.

There could also be a contribution to $t\overline{t}$ production from $\rho_8 \to \eta_0\mathcal{G}$. The color factors are such that the η_0 contribution to the cross section is two-fifths the contribution of an η_8 with the same mass. On the other hand for the mass ranges of the η_8 that we will be exploring in this talk, the mass of the η_0 may well be below the $t\overline{t}$ threshold. To be definite we will henceforth assume that only the η_8 contributes to the process of interest.

The CDF results on the top quark mass and production cross section are primarily based on detecting the $t\overline{t}$ pair in its leptons + jets decay mode. This would nominally produce events with four jets. However many of the events observed have five or more jets, as could be expected from QCD gluon radiation. For such events the procedure followed [2] is to assume that the four highest E_T jets arise from the decay of the $t\overline{t}$ system. Thus even events which have extra gluons are included in the CDF analysis, and hence our mechanism for the production of $t\overline{t}\mathcal{G}$ would contribute to their measurement of the $t\overline{t}$ cross section.

m_{ρ_8}	m_{η_8}	$\sigma(p\overline{p} \to \rho_8 \to t\overline{t} + \mathcal{G})$			$\sigma(p\overline{p} \to \eta_8 \to t\overline{t})$		
475	400	2.06	2.74	2.99	0.72	1.61	1.35
475	450	0.71	0.72	0.60	0.42	0.83	0.40
525	450	1.35	1.64	1.69	0.35	0.69	0.33
750	400	0.25	0.41	0.25	0.35	0.72	0.34

Table 1: Cross sections for the production of $t\overline{t} + \mathcal{G}$ at the Tevatron. For each set of masses, the first column under each cross section corresponds to $\{N = 2, k = 1.0\}$, the second to $\{N = 4, k = 1.0\}$ and the third to $\{N = 2, k = 0.1\}$. All masses are in GeV and all cross sections are in pb. No QCD corrections are included.

Before presenting the cross sections for $t\overline{t}$ production, we first show the partial widths for the various decay modes that are relevant to our calculations. The partial widths for the decay modes[1] of the ρ_8 can be calculated using the ideas outlined in [16, 17, 18] to be:

$$\Gamma(\rho_8 \to q\overline{q}) + \Gamma(\rho_8 \to \mathcal{G}\mathcal{G}) = \frac{5}{6}\frac{\alpha_s^2(m_{\rho_8})}{\alpha_{\rho_8}} m_{\rho_8} + \frac{1}{2}\frac{\alpha_s^2(m_{\rho_8})}{\alpha_{\rho_8}} m_{\rho_8} \,, \tag{1}$$

and

$$\Gamma(\rho_8 \to \eta_8 \mathcal{G}) = \frac{5}{128}\frac{1}{\pi^3}\left(\frac{N}{3}\right)^2 \frac{\alpha_{\rho_8}\alpha_s(m_{\rho_8})}{F_Q^2}\left(\frac{m_{\rho_8}^2 - m_{\eta_8}^2}{m_{\rho_8}}\right)^3 \tag{2}$$

Following [11], we have assumed the following scaling relations for α_{ρ_8}, the ρ_8 decay constant and F_Q, the analog of the pion decay constant

$$\begin{aligned} \alpha_{\rho_8} &= \frac{3}{N} 2.97 \\ \frac{F_Q}{m_{\rho_8}} &= \frac{f_\pi}{m_\rho}\sqrt{\frac{N}{3}} \end{aligned} \tag{3}$$

where 2.97 is the QCD ρ meson decay constant. N is the number of "colors" in this theory; if this were to be a technicolor theory then N would be the number of technicolors.

The decay widths of the η_8 are given by [9]

$$\Gamma(\eta_8 \to t\overline{t}) + \Gamma(\eta_8 \to \mathcal{G}\mathcal{G}) = k_t \frac{m_t^2 m_{\eta_8}}{16\pi F_Q^2}\sqrt{\left(1 - \frac{4m_t^2}{m_{\eta_8}^2}\right)} + \frac{5N^2\alpha_s m_{\eta_8}^3}{384\pi^3 F_Q^2} \,. \tag{4}$$

The constant of proportionality for the $t\overline{t}$ decay, k_t, is determined by some underlying theory and is expected to be of order one. In our calculations, k_t is varied between 0.1 and 1. The decay $\eta_8 \to t\overline{t}$ dominates over the decay into $\mathcal{G}\mathcal{G}$ except when m_{η_8} is very close to the $t\overline{t}$ threshold or when k_t is very small.

[1] We are assuming that the ρ_8 is below the two pseudo-Goldstone boson threshold.

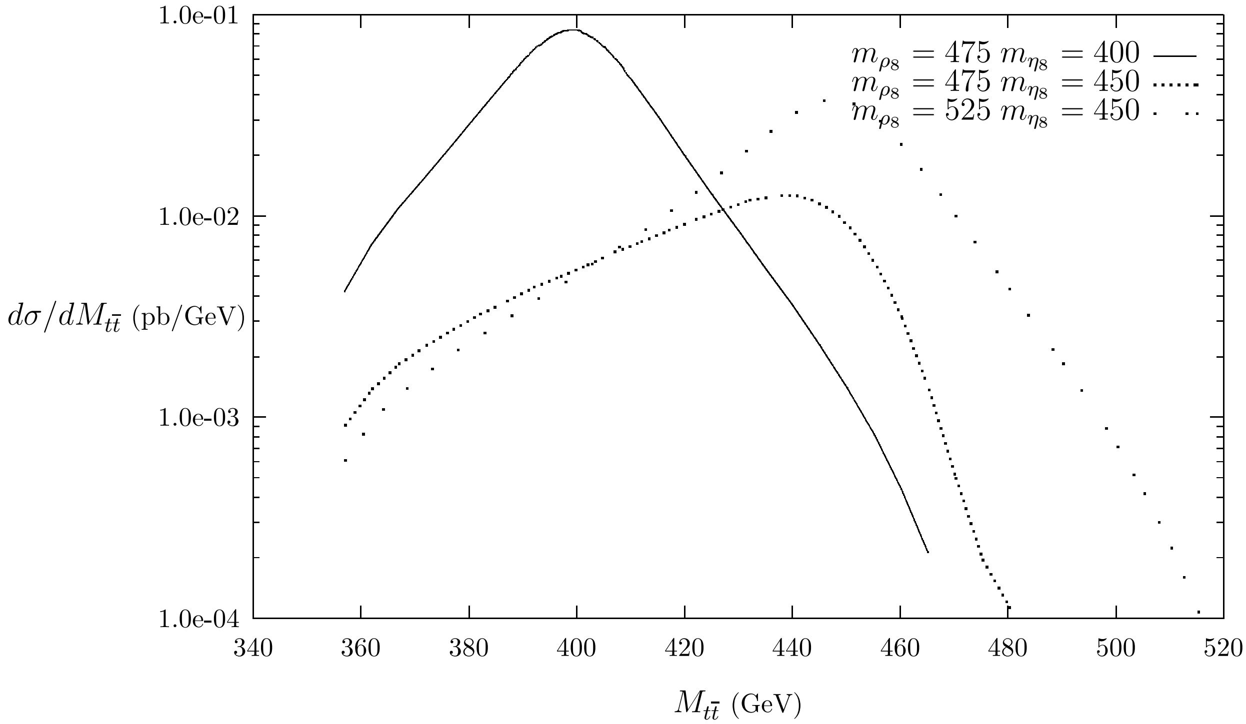

Figure 1: The differential cross section for total $t\bar{t}+\mathcal{G}$ production with $M_{t\bar{t}}$ being the invariant mass of $t\bar{t}$. No rapidity cuts are imposed. $N = 2$ and $k_t = 1$.

The resulting partonic level differential cross section for the process $q\bar{q} \to t\bar{t}\mathcal{G}$ is

$$\begin{aligned}\frac{d\hat{\sigma}}{dz dM_{t\bar{t}}} &= \frac{5}{384\pi^4}\left(\frac{N}{3}\right)^2 \frac{\alpha_s^3 k_t m_t^2}{F_Q^4} \frac{m_{\rho_8}^4}{((\hat{s}-m_{\rho_8}^2)^2+\hat{s}\Gamma_{\rho_8}^2)} \\ &\quad \left(1-\frac{M_{t\bar{t}}^2}{\hat{s}}\right)^2 \sqrt{\left(1-\frac{4m_t^2}{M_{t\bar{t}}^2}\right)} \frac{(M_{t\bar{t}}^2-2m_t^2)M_{t\bar{t}}}{((M_{t\bar{t}}^2-m_{\eta_8}^2)^2+M_{t\bar{t}}^2\Gamma_{\eta_8}^2)} (1+z^2)\,. \qquad (5)\end{aligned}$$

where $M_{t\bar{t}}$ is the invariant mass of the $t\bar{t}$ pair, $\hat{s}$, the partonic center of mass energy and $z = \cos(\theta)$ with θ being the angle between the outgoing gluon and the incoming quark. In view of the complexity of the top quark analysis followed by the CDF and D0 collaborations [2, 3, 19], no rapidity cuts are imposed on the top quarks. In order to be conservative, we also do not include any QCD corrections although they are expected to be significant, as in the case of $t\bar{t}$ production from QCD [4]. These corrections could easily increase the production rate by 50% or more.

This parton level result can be folded in with the quark distribution functions and integrated over $z = \cos(\theta)$ and $M_{t\bar{t}}$ in order to obtain the total production cross section for $t\bar{t}+\mathcal{G}$. We have ignored the contribution from $\mathcal{G}\mathcal{G} \to t\bar{t}+\mathcal{G}$ since the gluon structure functions are small at the Tevatron. The results of this computation are presented in Table 1 which shows the cross sections for $t\bar{t}$ production for different values of m_{ρ_8}, m_{η_8}, N and k_t. We have used the EHLQ set II structure functions [11] with $Q^2 = \hat{s}$ and have chosen values of m_{ρ_8}

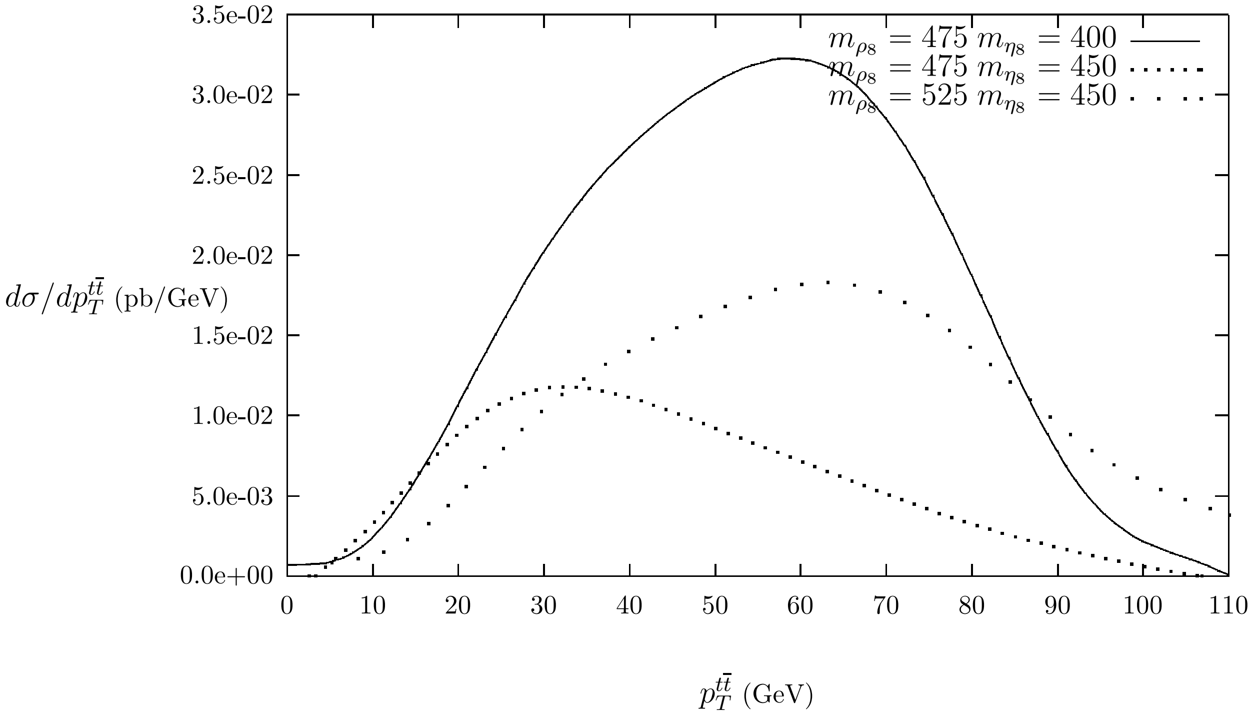

Figure 2: The $p_T^{t\bar{t}}$ distribution in $t\bar{t}+\mathcal{G}$ production. A rapidity cut of $y_c = 2.0$ is imposed on the final state gluon. $N = 2$ and $k_t = 1$.

consistent with the range excluded in [20].

The total cross section for $t\bar{t}$ production corresponds to events where the extra (hard) gluon may or may not be detected. For comparison, along with the cross sections for $p\overline{p} \to \rho_8 \to t\bar{t} + \mathcal{G}$, we also show the contribution from $p\overline{p} \to \eta_8 \to t\bar{t}$ using the formulae in [15] for the parameters we have chosen. However, unlike the authors of [15], we do not incorporate any estimates of QCD corrections.

The largest ρ_8 mass displayed in Table 1 is 750 GeV; this mass is beginning to approach a value more typical of standard technicolor theories. In this case, the contribution to top quark production from our mechanism is fairly small (about 5% or less of the estimated cross section). However these events would have a unique signature — a $t\bar{t}$ pair with large p_T recoiling against a high energy gluon.

For the lower m_{ρ_8} values we consider in more detail methods to distinguish our contribution to top quark production from the standard model contribution. In order to do this we focus on three different distributions — the invariant mass $M_{t\bar{t}}$ and the transverse momentum $p_T^{t\bar{t}}$ of the $t\bar{t}$ pair, and the total invariant mass M_{inv} of $t\bar{t}+\mathcal{G}$. These distributions are plotted Figures (1-3) for the parameter values : $\{m_{\rho_8} = 475\,\mathrm{GeV}\,,\ m_{\eta_8} = 400\,\mathrm{GeV}\,\}$, $\{m_{\rho_8} = 475\,\mathrm{GeV}\,,\ m_{\eta_8} = 450\,\mathrm{GeV}\,\}$ and $\{m_{\rho_8} = 525\,\mathrm{GeV}\,,\ m_{\eta_8} = 450\,\mathrm{GeV}\,\}$.

The differential cross section $d\hat{\sigma}/dM_{t\bar{t}}$ is displayed in Fig. 1. Since we are interested in

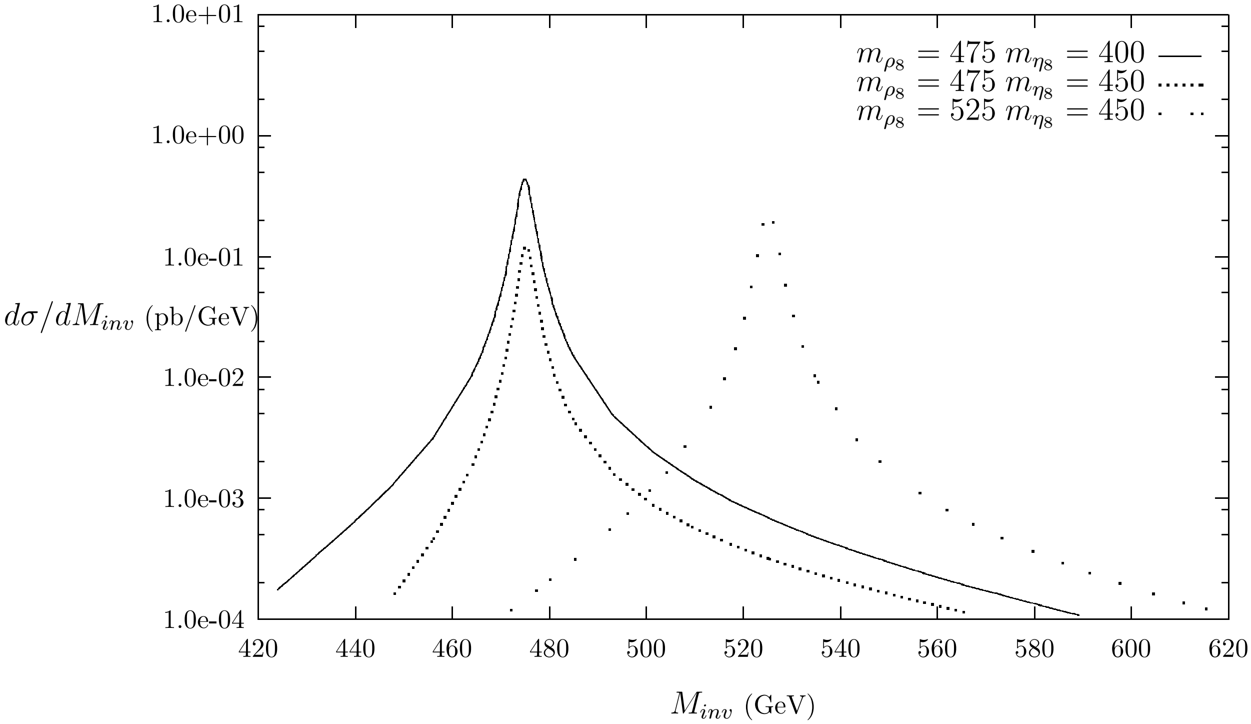

Figure 3: The differential cross section for $t\bar{t} + \mathcal{G}$ production with M_{inv} being the invariant mass of $t\bar{t} + \mathcal{G}$. A rapidity cut of $y_c = 2.0$ is imposed on the final state gluon. $N = 2$ and $k_t = 1$.

estimating the total top quark production, we have not imposed any rapidity cuts on the gluon. As expected, there is a peak in the $M_{t\bar{t}}$ distribution due to the intermediate resonance, the η_8. However for heavier η_8, the $M_{t\bar{t}}$ distribution is quite broad and the peak may not show up very cleanly.

Another variable of interest for new physics is the transverse momentum of the $t\bar{t}$ pair $p_T^{t\bar{t}}$. We show the distribution from our mechanism in Fig. 2. In calculating this distribution (and the one in Fig. 3) we impose a rapidity cut of $y_c = 2.0$, so that the gluon be within the ambit of the detector. This is the value used by the CDF collaboration [19]; we found that this cut reduced the total event rates by about ten to fifteen percent. The standard model $p_T^{t\bar{t}}$ distribution has been obtained [21] using both next-to-leading order QCD calculations and HERWIG simulations. Similarly the p_T distribution for gluons radiated in $t\bar{t}$ production has been calculated [22]. The distribution peaks for $p_T^{t\bar{t}}$ around 5 GeV and then falls rapidly for increasing $p_T^{t\bar{t}}$. A significant excess of high p_T $t\bar{t}$ pairs would signal a nonstandard production mechanism.

The $p_T^{t\bar{t}}$ distribution is closely related to the distribution of the quantity referred to as X in [19]. This is the total *observed* transverse energy remaining in the event after subtracting vectorially the transverse energy of the four jets and the charged lepton. The X values for the seven events used for mass fitting in [19] are {7.1 GeV, 7.7 GeV, 14.8 GeV, 17.0 GeV,

20.0 GeV, 26.3 GeV and 35.6 GeV}. A larger data set is clearly required before any serious analysis can be made.

We notice that there is a significant bias in the extraction of X which distorts its interpretation as a measure of $p_T^{t\bar{t}}$. The method [2] used in deciding which of the jets in an event come from top decays is to assign the four highest energy jets to the decay of the $t\bar{t}$ system. While this is suitable for standard model $t\bar{t}$ production, it may not be appropriate if one wishes to allow for new physics. In particular, the hard gluon produced in our mechanism can be mistakenly assigned as one of the jets from the $t\bar{t}$ system. This in turn could distort the extraction of the top mass. It also implies that the observed X distribution is likely to be softer than the true $p_T^{t\bar{t}}$ distribution.

The third variable we consider is the total invariant mass of the event, which in our case is the invariant mass of the $t\bar{t} + \mathcal{G}$. Since the ρ_8 is relatively narrow this distribution is sharply peaked, as can be seen in Fig. 3. This variable is also less prone to experimental ambiguities involved in assigning jets to underlying partons.

In conclusion, we have suggested a mechanism for the production of top quarks at the Tevatron. The ρ_8 and η_8 resonances which take part in this resonant enhancement of $t\bar{t}$ events are generic of any strongly interacting theory with at least one colored, electroweak doublet of fermions. If these resonances have masses in the range of 400-550 GeV range, they can contribute significantly to $t\bar{t}$ production at the Tevatron. We have suggested ways of distinguishing this mechanism from standard model production. We finally note that if the color-singlet η_0 was also above the top-pair threshold then we would have contributions from both the η_8 and the η_0. There would be two peaks in the $M_{t\bar{t}}$ distribution, with their relative contributions being fixed by the masses of the resonances.

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